

# Diode-Pumped 1-W Continuous-Wave Er:YAG 3- $\mu$ m Laser

15 June 1999

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A handwritten signature in cursive script, reading "Holliston Shankle", positioned above a horizontal line.

Holliston Shankle  
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13. ABSTRACT (Maximum 200 words)  We have demonstrated 1.15 W of Gaussianlike ( $M^2 = 2$ ) cw output at 2.94 μm from a diode laser end-pumped monolithic laser crystal composed of Er-doped yttrium aluminum garnet (YAG) bonded to undoped YAG. The laser was pumped with two polarization-coupled 2.5 W flared laser diodes that provided a 45-μm pump waist with a low N.A. (<0.04). Output at 2.94 μm was generated with a 34% slope efficiency and a greater-than-unity quantum efficiency.				
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Recent interest in the development of Er-doped solid-state lasers for high-intensity 3- $\mu\text{m}$  sources has been fueled predominantly by the medical community because of the strong absorption by water in this wavelength range. Er-doped yttrium aluminum garnet (Er:YAG), however, has a transition at 2.94  $\mu\text{m}$  that fortuitously overlaps one of the few transmission bands in the water-vapor spectrum in the 3- $\mu\text{m}$  range and is therefore useful for meteorological and special metrology applications. Until now, the highest reported cw output power from diode-pumped Er:YAG at 2.94  $\mu\text{m}$  was 171 mW, which was obtained with a 12% slope efficiency ( $\eta$ ).<sup>1</sup> Our efforts have yielded 1.15-W output and  $\eta$  of 34%. To the best of our knowledge, this is the highest efficiency and diode-pumped cw Er<sup>3+</sup> laser output near 3  $\mu\text{m}$ .<sup>1-6</sup>

Previously, the cw operation of other Er-doped hosts had exceeded that of Er:YAG. Stoneman and Esterowitz<sup>2</sup> reported 125-mW output ( $\eta = 36\%$ ) from Ti:sapphire-pumped Er-doped gadolinium scandium gallium garnet (Er:GSGG), while Dinerman and Moulton<sup>5</sup> obtained 0.5-W output from diode-pumped Er-doped yttrium scandium gallium garnet (Er:YSGG) ( $\eta = 31\%$ ). The rather high  $\eta$  for Er:GSGG corresponded to a greater-than-unity quantum efficiency, which demonstrated for the first time that photons were recycled during the upconversion process for the  $^4I_{11/2} - ^4I_{13/2}$  transition of Er<sup>3+</sup>. A high cw slope efficiency ( $\eta = 35\%$ ) was also demonstrated for Er-doped yttrium lithium fluoride (Er:YLF) at the 400-mW level by Jensen *et al.*,<sup>6</sup> using polarization-coupled pump diodes. They also reported 1.1-W cw output ( $\eta = 20\%$ ) from the same crystal, using a fiber-coupled diode bar as the pump source. The total Er:YLF laser output was not directly measured, because the laser emitted from both reflectors.<sup>6</sup>

The lower efficiency of Er:YAG compared with that of other garnets, such as Er:GSGG and Er:YSGG, has been attributed to the unfavorable lifetimes of the upper and lower laser levels<sup>7</sup> and to the lower stimulated-emission cross section of Er:YAG.<sup>8</sup> The issues for achieving lasing from the  $^4I_{11/2} - ^4I_{13/2}$  transition of Er<sup>3+</sup> and the less favorable properties of Er:YAG than those of other hosts have been discussed at some length in the literature.<sup>9</sup> Because the Stark sublevel dynamics are different for each Er<sup>3+</sup> host, conditions (temperature, pump specifications, and feedback or coatings) for

achieving high output from a specific lasing transition are unique to each crystal. Before this report, we undertook a comprehensive study comparing the performance of many crystal configurations with varied doping percentages, coating properties, pump wavelengths, and pump waists. Combining the results with the reported work of others, we were able to specify crystal properties (dimensions, coatings, and configuration) and pump-laser characteristics to achieve greater than 1 W of cw output at 2.94  $\mu\text{m}$  from an Er:YAG laser.

Both in this study and in earlier work, it was determined that a short (few-millimeter) monolithic crystal resonator design using a longitudinal pump laser as an excitation source could best optimize the low-gain and high-pump-absorption properties of the 3- $\mu\text{m}$  Er:YAG laser. Our earlier end-pumping laser measurements using a Ti:sapphire laser showed that monolithic Er:YAG crystals processed in different coating runs could lase at either 2.83 or 2.94  $\mu\text{m}$  or both. The sensitivity of the output wavelength to coating reflectivity and pump characteristics can be attributed to the slight variation in the emission cross sections<sup>8</sup> and the saturation properties<sup>10</sup> for the two transitions. It was concluded that for optimum cw output at 2.94  $\mu\text{m}$  the output coupler (OC) must have a reflectivity greater than 99.6% at 2.94  $\mu\text{m}$  and a lower reflectivity at 2.83  $\mu\text{m}$ . Ti:sapphire end-pumping measurements also indicated the importance of achieving a high pump-power density. Early data indicated that the slope efficiency increased as a function of decreasing pump waist. In most cases in which the OC reflectivity was less than 99.6%, efficient conversion was achieved for pump waists (radii) less than 50  $\mu\text{m}$ . However, the combination of high pump power and intracavity intensity resulted in damage to the high reflector (HR) in nearly every sample previously tested. To eliminate this damage condition, we configured the crystals with the HR on an undoped section of YAG. This composite approach not only distances the HR from the point of maximum intensity and thermal loading but also reduces the peak temperature,<sup>11-13</sup> which is particularly beneficial to lasers with temperature-sensitive transitions. The composite crystals were configured with a 1-mm section of undoped YAG on the pump side that was diffusion bonded to either 1- or 2-mm-thick 50%-doped Er:YAG, yielding

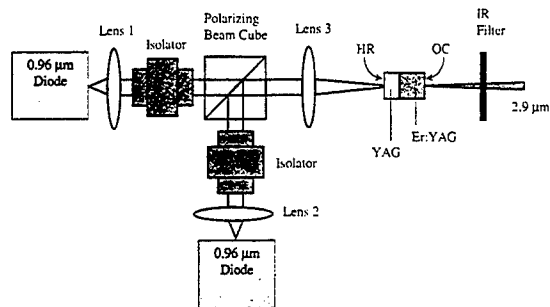


Fig. 1. Schematic illustration of the diode-pumped Er:YAG experimental layout.

total cavity lengths of 2 and 3 mm, respectively (Fig. 1). All the crystals had a 3 mm by 3 mm cross section and flat HR's. The OC's were either flat or concave, with radii of 1 and 4 cm for the 3- and 2-mm samples, respectively.

To achieve high efficiency at 2.94  $\mu\text{m}$  and suppress output at 2.83  $\mu\text{m}$ , tight specifications on the optical coatings were necessary. The high-reflection high-transmission coating on the pump side of the crystal required reflectivity  $R > 99.95\%$  at 2.94  $\mu\text{m}$ ,  $R < 99.9\%$  at 2.83  $\mu\text{m}$ , and transmittivity  $T \geq 90\%$  at 964-nm pump wavelength. The OC coating needed to have  $R = 99.8 \pm 0.05\%$  at 2.94  $\mu\text{m}$  and a significant reflectivity ( $R \geq 95\%$ ) at the 964-nm wavelength for double-pass pumping. Finally, the combined loss at 2.83  $\mu\text{m}$  of the HR and the OC had to be greater than at 2.94  $\mu\text{m}$ . The spectra of the HR and the OC (Fig. 2) coatings provided by the vendor indicated that they met all our requirements. The reflectivities of the OC and the HR were 99.85% and 99.96% at 2.94  $\mu\text{m}$ , 99.65% and 99.82% at 2.83  $\mu\text{m}$ , and 10% and 95% at 964 nm. As a result, the combined reflectivity loss at 2.94  $\mu\text{m}$  was significantly lower than at 2.83  $\mu\text{m}$  (i.e., 0.19% versus 0.53%).

To focus several watts of pump power within the small laser mode volume, we polarization combined two novel diffraction-limited laser diode devices. The laser devices were developed by SDL, Inc., and consisted of a tapered InGaAs gain element and an external grating for wavelength-stabilization control.<sup>14</sup> These devices were also fitted with an optical isolator so that stable single-frequency diffraction-limited output was provided. The outputs of the two devices at 963.7 and 964.2 nm were combined and collimated to form a 1.8-mm-diameter beam. This beam was then focused into the Er:YAG crystal with a 5-cm focal-length lens. The resultant pump beam had a N.A. of  $<0.04$  and a pump waist of 45  $\mu\text{m}$ . The schematic layout is shown in Fig. 1.

The initial results consistently showed a 30–40% higher output power for the 3-mm samples than for the 2-mm samples when the pump power was limited to less than 2.5 W of incident power. Representative performance curves for the crystals (without temperature control) are shown in Fig. 3. The efficiency of the flat-flat (FL/FL) samples was typically higher than that of the flat-curved (FL/1 cm, FL/4 cm) samples,

although the flat-curved samples demonstrated lower thresholds regardless of the crystal thickness. The lower thresholds on the flat-curved samples suggest that the effective waist is smaller for the flat-curved samples than for the flat-flat samples. The flat-flat samples had the additional advantage of being less sensitive to positioning of the pump laser for achieving optimum performance than the flat-curved samples. During these preliminary tests, we also observed that the output power increased at a rate of  $\sim 3 \text{ mW}/^\circ\text{C}$  as the sample temperature decreased.

We selected the best-performing sample, a 3-mm flat-flat crystal, and cooled it to 15  $^\circ\text{C}$  both to optimize performance yet avoid water condensation. At a maximum incident diode pump power of 4.4 W, 1.15 W of output power at 2.94  $\mu\text{m}$  was obtained. At this power level the diode lasers required 18 W of electrical power, yielding a total laser electrical efficiency of 6.4% (not including the power to the thermoelectric coolers). No coating damage was observed at this power level or in any of the tests of the bonded samples discussed above. The laser output beam quality was measured to have an  $M^2$  of  $\sim 2$  and did not vary significantly at the various power levels. Only 2.94- $\mu\text{m}$  lasing output was observed at all pump powers. The HR reflectivity at the pump wavelength was measured to be 10%. Measurements of the OC coating reflectivity at the pump wavelength (94%) and the single-pass

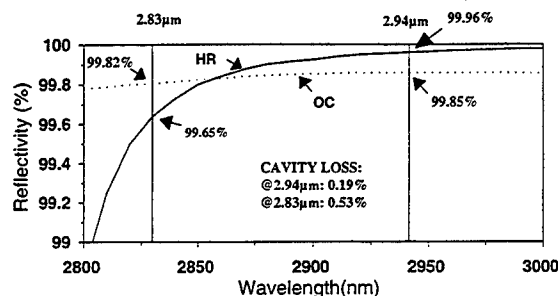


Fig. 2. Coating reflectivity of Er:YAG samples. HR, reflectivity curve for the pumping surface; OC, reflectivity curve for the output surface.

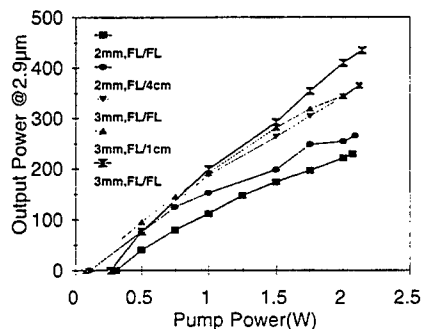


Fig. 3. Er:YAG output performance from various samples pumped by one diode under the same conditions. The legend indicates sample's cavity length and curvatures of the HR and the OC.

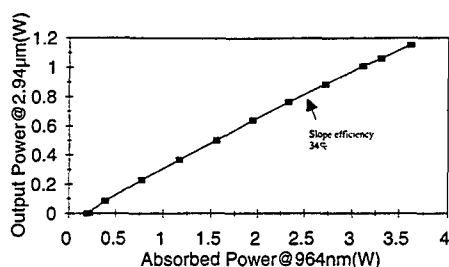


Fig. 4. Diode-pumped laser output power at  $2.94\ \mu\text{m}$  from a 3-mm flat-flat sample versus absorbed pump power.

absorption of an uncoated 2-mm Er:YAG sample (70%) indicated that the double-pass absorption in the 3-mm coated flat-flat sample was 90%. When the coating loss and the absorbed power are taken into account, the effective slope efficiency is 34%, corresponding to a greater-than-unity quantum efficiency. The performance of this crystal is shown in Fig. 4, in which the output power versus the absorbed pump power is plotted.

In summary, we have demonstrated 1.15-W cw diode-pumped Er:YAG laser output at  $2.94\ \mu\text{m}$  at greater-than-unity quantum efficiency. Well-defined and well-executed optical coatings on end-pumped Er:YAG monolithic crystals control not only the laser efficiency but also the lasing wavelengths. The combination of a well-designed coating and the implementation of an undoped section optically bonded at the pump end appears to have mitigated the problem of optical coating damage observed in earlier studies.

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August 31, 1999

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Dear Defense Technical Information Center :

In regard to Aerospace Report No. TR-99(1019)-1, "Diode Pumped 1-W Continuous-Wave Er:YAG 3 $\mu$ m Laser."

The Air Force (SMC) report number on the referenced report is in error. The AF number, SMC-TR-99-20 should read SMC-TR-99-21.

Please make the change to your copy of the report.

Sincerely,

Jack Shaffer  
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M/S M2-273

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